

Sizing Up Nanotechnology

by Kristine Mak-Yu

The next big thing

The Meaning of Nanotechnology

It's easy to define and describe a nanometer: a nanometer is a billionth of a meter. That's a millionth of a pinhead, a thousandth of a red blood cell diameter, or the length of a line of ten hydrogen atoms rubbing shoulders. If only knowing what nanotechnology really means were as simple: "Have you heard the story of the elephant and the blind man?" Professor Krishna Saraswat chuckles. "Nanotechnology has different meanings to different people, but the conventional definition is the science of material patterned at the 1-100 nm length scale," notes Professor Michael McGehee. Professor Chris Chidsey muses, "Nanotechnology is a concept that is largely designed to capture people's imagination rather than describe a particular type of research. It's largely an attempt to portray a unified vision for a pretty wide-ranging group of activities that might not otherwise get recognized."

As a term, nanotechnology is clearly ambiguous. Moreover, it has already been claimed by the Drexlerians, apostles of K. Eric Drexler, who was one of the first to popularize nanotechnology with the publication of his 1987 book, *Engineers of Creation: The Coming Era of Nanotechnology*. According to Professor Steve Block, the Drexlerians have a futurist vision of nanotechnology in which self-replicating molecular assemblers programmed at the molecular-scale manufacture arbitrary products at the atomic level, molecule by molecule, bottom up. Some scientists have attempted to distance themselves from the futurist Drexlerians by claiming the term nanoscience. There's also another motivation for the excision of "technology" in this term. Nanoscience, as a term, captures the learning—the fundamental understanding of processes

and materials at the nanoscale—that many scientists feel is necessary before or at the same time that researchers turn to engineering solutions. The term nanotechnology, on the other hand, reinforces what Chidsey describes as a "glib attitude" that "technology is the goal of science at this length scale."

Yet, there remains a problem with the "nano" in both nanoscience and nanotechnology. "Nanotechnology's a term with not too much new in it. It existed a long time ago," says Dai. Indeed, the characteristic length of bonds that have always been under scrutiny in the molecular sciences is on the order of a nanometer. Chidsey adds, "I worry that the term confuses people about what's important: the length scale itself is not important." Rather, it is the novel properties that structures exhibit at the nanoscale that is. As Dai puts it, "We work on carbon nanotubes not because they are small, but because they are interesting. They just happen to be nano." For all the problems with the term nanotechnology, though, it may have done some good. Chidsey remarks, "Just as nanotechnology has attracted the attention of outsiders, it also stimulates us internally: it provides a context for tackling and defining grand challenges—things so out there you wouldn't tackle them otherwise."

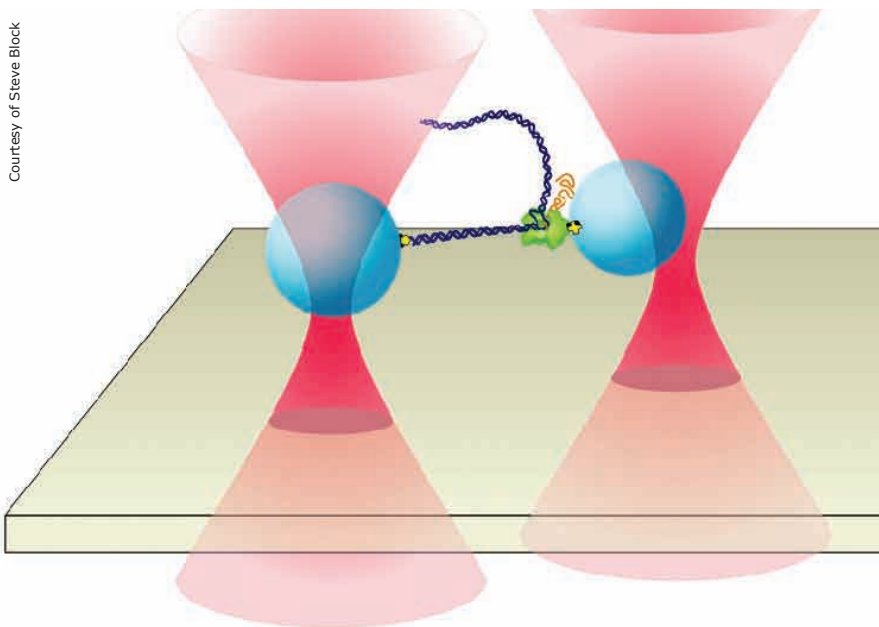
All over campus, Stanford has eagerly embraced the "grand challenges" of nanotechnology. Just this April, the Stanford Nanofabrication Facility (SNF) hosted an open house to celebrate its selection to be part of the National Science Foundation-sponsored National Nanotechnology Infrastructure Network sprawling across thirteen universities nationwide. Along with the new Nanocharacterization Laboratory expanding the SNF, the nearly finished Manoharan lab that Stanford students bike past on the way to physics lab embodies the prominent place nanotechnology has in Stanford research for years to come. Specifically, the Manoharan lab is equipped to manipulate matter on an atomic level. Here's a cross-section of nanotechnology research currently being pursued at Stanford:

Here's To Biology: Nature's Own Nanomachines

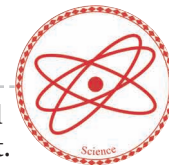
Dr. Steve Block, Biology and Applied Physics

In your brain right now, a motor protein called kinesin is shuttling vesicles loaded with neurotransmitters to the synapses in your brain, allowing you to read this. While some researchers are trying to make similar molecular motors scoot around and throw switches on electronic chips, it's hardly certain these motors can ever do better than the electrical contacts that are routinely used today. The future of biological nanotechnology may not be clear, but what is, says Professor

Courtesy of Steve Block



The backtracking movement of RNA polymerase can be followed using optical tweezers.



Block, is that “if we are ever to build machines which are in any way based on biological structures, then we will have to learn about how real biological systems function.”

Nature’s own marvelous nanoscale machines include motors that spin bacterial flagella at up to 1000 revolutions per second and polymerases that step along DNA and RNA to facilitate the flow of genetic information. Block, along with other Stanford researchers such as Professors W. E. Moerner (Chemistry) and Steve Chu (Physics), are studying Nature’s machines through single molecule science. This young field is devoted to following molecules one at a time rather than observing their averaged behavior, as has been done traditionally. To understand why average properties may obscure molecular behavior, “Consider a ship traveling from New York to San Francisco,” says Block. “If it’s small enough, it will travel down into the Caribbean and go across the Panama Canal and then back up to San Francisco. If it’s a big oil tanker, it won’t fit through the Panama Canal; it’s got to go all the way around Cape Horn. But the *average* path of a ship traveling from New York to San Francisco would probably come out somewhere in the middle of the Amazon where there is in fact no route at all!”

To study single molecules, Block has pioneered the use of optical tweezers, tiny laser-based “tractor beams” that produce miniscule piconewton forces to drag around molecules and allow measurements of displacements on the order of a nanometer. “You can stop and stall molecules, w follow their motion. Recently, we’ve studied the backtracking of RNA polymerase: when it makes a mistake, it can actually back up by five bases, scoop off the wrong thing and start again,” says Block. While biological nanotechnology “hasn’t even arrived at its infancy yet,” says Block, “biological nanoscience is a very exciting place to be right now, because the techniques now exist to truly study proteins, and we’re learning so much about them.”

Energy: Self-Assembling Solar Cells

Dr. Michael McGehee, Materials Science and Engineering

As the global energy demand continues to rise, the need for renewable energy sources has become ever more urgent. One candidate fuel for the future is hydrogen. Professor McGehee is hot on the trail, developing solar cells to generate electricity, which can then be used to zap water apart electrolytically into hydrogen (and oxygen) with 80% efficiency.

While sunlight is cheap, harnessing it is currently too expensive to be worthwhile on a large scale. For four years, McGehee and his graduate students have been working to make it cheaper to convert sunlight into electricity. While the silicon-based solar cells currently used generate electricity at

\$3/Watt, McGehee is aiming for nanostructured solar cells that are ten times cheaper at \$.30/Watt. Once fully developed, McGehee’s solar cells would be lower cost because the materials are cheaper. Moreover, they would be more lightweight and flexible so that “you could roll them out over rooftops,” says McGehee.

McGehee makes his solar cells by mixing a titania gel



Professor Michael McGehee is developing cheap and efficient nanostructured solar cells.

precursor and a special semiconducting polymer, which self-assemble into titania (TiO_2) films with polymer-filled pores 20 nm in diameter. Currently, McGehee is still working to improve the efficiency of his solar cells and their resistance to degradation over time in sunlight. “Right now, we’re at 2% efficiency, and we want to get to 15%.” 15%? That might seem low, but silicon-based cells operate at 12% efficiency, and most importantly, as McGehee points out, “there’s a lot of sunlight out there.”

Materials: Carbon Nanotubes

Dr. Hongjie Dai, Chemistry

Slice a layer of pencil lead, roll it up, and you have a carbon nanotube: a graphene sheet (a layer of graphite) rolled up into a cylinder. “A carbon nanotube is a clever way of making a fully saturated nanowire structure—a 1-D structure with all its atoms fully bonded,” explains Professor Dai, who has developed catalysts that control where carbon nanotubes grow. “The big challenge is controlling the synthesis. More control leads to definite physical properties,” says Dai. In contrast to conventional semi-conductors, where “the surface atoms are not happily bonded,” as Dai puts it, the high degree of structural perfection in nanotubes leads to ballistic transport of electrons, which translates into high speed electronics. Dai predicts that while it is doubtful that carbon nanotubes will overtake the electronics industry, it is quite possible that they will replace some electronics components.

In other applications of carbon nanotubes, Dai has

successfully demonstrated their use as highly sensitive toxic gas sensors, and with Professor Calvin Quate (Electrical Engineering), has commercialized nanotubes as scanning probe tips to increase probe resolution and tip durability. An area that Dai has just begun exploring is the drug delivery potential of carbon nanotubes. “The tube has a large surface area and is empty inside. So either you can attach the drug to the outer surface, or fill it up like a test tube,” says Dai. Furthermore, multiple functional molecules can be attached to the surface: “Say, a molecule that fluoresces to tell you where the drug is in the cell and an antibody that specifically targets the site of drug delivery.” So far, Dai reports that his research finds nanotubes to be quite “biologically friendly.”

All this from pencil lead: “graphite is a very old material, but take a tiny tube of graphite and it has totally different properties, says Dai. “That’s what nanotech is all about.”



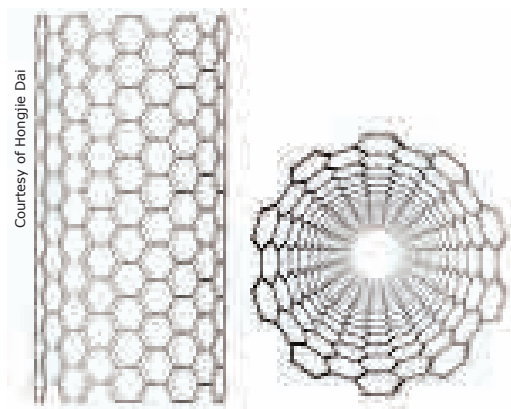
Dr. Krishna Saraswat

Courtesy of Krishna Saraswat

Electronics: Building Chips in 3-D

Dr. Krishna Saraswat, Electronic Engineering; Dr. Chris Chidsey, Chemistry

“Whether nanotechnology had ever showed up or not, electronics would have gotten there anyway,” says Professor Saraswat. For the past four decades, the number of transistors that can be put on a chip, or equivalently, the number of information processing events that can be done per chip, has doubled every twenty-two months; concomitantly, the cost per processing event has dropped. Following this trend called Moore’s Law, microelectronics has steadily settled into nanoelectronics in the past decade.



Courtesy of Hongjie Dai

Currently, the gate length, the characteristic length parameter in transistors, has hit about 90 nm. The shorter the gate length, the faster transistors can switch on and off. In fact, the transistors have gotten so fast, that the delay as electrons flow through the skinnier and longer wires needed to cross larger, complex chips is on track to become

the limiting factor in speed. This delay is just one of the fundamental problems that threatens to make the nanoscale regime of electronics unfaithful to Moore’s Law and demands the design of new materials and structures or a complete shift in chip architecture.

A decade ago, Saraswat’s research group was the first to begin developing a new kind of chip architecture: the 3-dimensional integrated circuit (3-D IC). Compared to the 2-D planar chips in computers today, 3-D chips can provide the same processing power with a reduced chip surface area. Also, instead of having long, twisting highways of wires, the stacked chips in 3-D ICs allow for short wires much like elevator shafts, as Professor Chidsey puts it—mitigating the problem of delay in the wires.

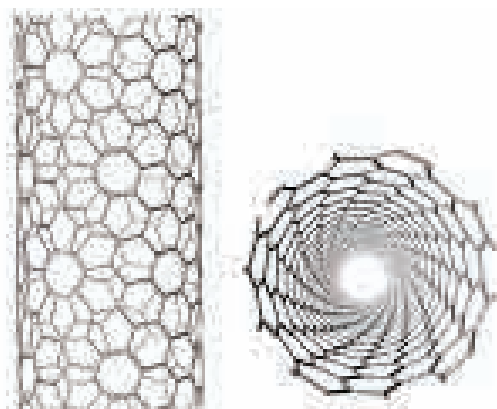


Dr. Chris Chidsey

Moreover, 3-D IC architecture allows the integration of all kinds of chips, since chips that require different technologies or materials can be stacked together.

The main challenge in 3-D IC design is performance-weakening heat dissipation, which is already a problem in 2-D chips, as any Stanford students who have written a term paper with their laptops on their laps know. The multi-layer design of 3-D ICs exacerbates the problem, and Mechanical Engineering Professors Ken Goodson and Tom Kenney have been working on flowing fluid through microchannels incorporated in the chips to conduct the heat away.

Just this April, a large cross-departmental group of Stanford faculty was awarded a multi-million dollar grant to take up such challenges and develop new devices and technology for use in 3-D ICs. Chidsey, for instance, is one of the researchers involved in integrating nanowire



An area that Dai has just begun exploring is the drug delivery potential of carbon nanotubes.

transistors into 3-D circuits, which requires being able to position nanowires reliably and accurately. With the development of 3-D ICs, you can expect all-in-one MP3 player-telephone-digital camera-PDA devices the size of Star Trek communicators to hit the shelves at Fry’s within this decade. **S**